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# Big Bang Nucleosynthesis, Cosmic Microwave Background Anisotropies and Dark Energy

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**Abstract.** Over the last decade, cosmological observations have attained a level of precision which allows for very detailed comparison with theoretical predictions. We are beginning to learn the answers to some fundamental questions, using information contained in Cosmic Microwave Background Anisotropy (CMBA) data.

In this talk, we briefly review some studies of the current and prospected constraints imposed by CMBA measurements on the neutrino physics and on the dark energy. As it was already announced by Scott [1], we present some possible *new physics* from the Cosmic Microwave Background (CMB).

## 1 Introduction

Since the 80's, cosmologists introduce for the baryonic density ( $\rho_b$  or  $\Omega_b$ ) of the Universe, a concordance interval where predicted and measured abundances of light elements ( ${}^7\text{Li}$ ,  ${}^4\text{He}$ ,  $D$ ) were consistent, within their uncertainties. At the end of 90's, the determination of primeval  $D$  is supposed to be accurate enough to pin down  $\rho_b$  or  $\Omega_b$ ; and the *concordance intervals* for  $D$ ,  ${}^7\text{Li}$ ,  ${}^4\text{He}$  and  $\Omega_b$  were predicted by  $D$  measurements, see Burles et al. [2] and Signore-Puy [3]. Fig. (1) shows this problem of concordance from the works of Burles-Nollett-Turner [2].

In the year 2000, observations of CMBA have become a competitive means for estimating  $\Omega_b$ . Then CMBA results can be a cross check of Big Bang nucleosynthesis (BBN) results and can lead also to new constraints on BBN theory,

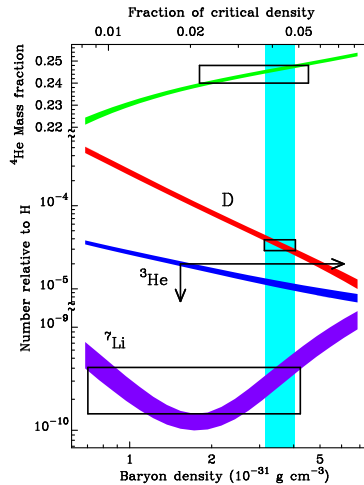


Figure 1: The situation of BBN in 1999. It shows the concordance intervals for each element ( $2\sigma$  uncertainties) and the baryon density predicted by primordial deuterium measurements, from Burles-Nollett-Turner [2].

ie neutrino physics.

On the other hand from observations of type Ia-supernova at high  $z$  carried out by two major teams -*Supernovae Cosmology Project* [4] and *High- $z$  Supernovae Team* [5]- there is some direct evidence that the present Universe is accelerating. For a pedagogical and recent review on this subject see [6] and references therein. Moreover, recent measurements of CMBA and of baryon fraction in galaxy clusters indicate that the Universe is flat and that the matter contributes about one third of the critical density  $\Omega_M \sim 1/3$ ; and about two thirds of the critical density constitutes the *dark energy*:  $\Omega_\Lambda \sim 2/3$ . The nature of this dark energy is the new challenge for cosmology and fundamental physics. Now, an important question is: besides the *SNIa experiments* (see SNAP [7]), can CMBA measurements provide constraints on the nature of the dark energy?

## 2 Constraints on Neutrino Physics

As already said above, until recently, BBN -from observations of primordial  $D$  abundances- provided the only precision estimates of  $\Omega_b$ . Considering the most recent primordial deuterium data, Burles, Nollett and Turner [8] give:

$$\Omega_b h^2 = 0.017 - 0.024 \quad (95\% \text{ CL}) \quad (1)$$

where  $h$  is the Hubble parameter in units of  $100 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ . In the past year, the first results which may rightly be called precision CMBA measurements

have been obtained from BOOMERANG [9] and MAXIMA [10]. A higher baryon density than that predicted from BBN has been claimed:

$$\Omega_b h^2 \sim 0.03. \quad (2)$$

The discrepancy between BBN and CMBA estimates for  $\Omega_b$  led to the suggestions that one must consider some *new physics* which appeared between the BBN epoch ( $T \sim 1$  MeV) and the CMB epoch ( $T \sim 1$  eV) in order to understand these different values of  $\Omega_b$  ([11], [12], [13], [14], [15]).

But the more recent data from BOOMERANG [16], MAXIMA [17] and DASI [18] show that there is no more difference between BBN and CMBA estimates for  $\Omega_b$ :

$$\Omega_b h^2 = 0.02, \quad (3)$$

and therefore no need of *new physics* to reconcile BBN and CMBA data. However, some cosmologists, in particular Kneller et al. [19], Hannestad [20], Hansen et al. [21] consider these CMBA data sets of high precision to constrain, independently of BBN, this *new physics*, that is to say the *neutrino physics*.

## 2.1 BBN limit on $N_\nu$

First, let us introduce  $N_\nu$  - the equivalent number of standard model neutrino species- through the energy density  $\rho$ :

$$N_\nu \equiv \frac{\rho}{\rho_{\nu_o}} \quad (4)$$

where  $\rho_{\nu_o}$  is the energy density of a standard neutrino species. This is a way of expressing the energy density in light non-interacting species. As noted in [20], the standard model predicts:

$$N_\nu \sim 3.04 \quad (5)$$

due to the fact that the neutrinos are not completely decoupled during the  $e^+ - e^-$  annihilation; see Steigman [22] for a detailed neutrino counting and a discussion on the above value, Eq. (5). The abundances of primordial  ${}^4\text{He}$ ,  $D$ ,  ${}^7\text{Li}$  can be used to determine BBN limit on  $N_\nu$ . For example, Lisi et al. [23] give the following bound adopted also by [20]:

$$3 \leq N_{\nu, \text{BBN}} \leq 4 \text{ (95\% CL)}. \quad (6)$$

Let us also mention the work done by Kneller et al. [19] who consider for BBN predictions the three parameters  $\eta$  -the baryon to photon ratio ( $\eta_{10} = 10^{10} \times \eta = 274 \Omega_b h^2 - \Delta N_\nu$  the asymmetrical part (or degenerate part) of  $N_\nu$  and  $\xi_\nu \equiv \mu_\nu / T_\nu$  where  $\mu_\nu$  and  $T_\nu$  are respectively the chemical potential and the temperature of the  $\nu$ -species.

## 2.2 CMBA limit on $N_\nu$

A bound on  $N_\nu$  has also been derived from CMBA data by many authors [19] [20] [21]. Let us only summarize the main points of these studies:

- *i)* Kneller et al. [19] used the CMFAST software [24] in order to calculate the cosmic background fluctuation spectrum as a function of  $\eta$  and  $\Delta N_\nu$  and compare to BOOMERANG [16], MAXIMA [17] and DASI [18] observations for four different cosmological models. They show, in the  $(\eta - \Delta N_\nu)$  plane, the four very different shapes of the confidence interval contours corresponding to the four cosmological models. Their results point out the sensitivity of the *new physics* ( $\Delta N_\nu$ ) to the other cosmological parameters.
- *ii)* The analysis of the CMBA data by three groups [19], [20], [21] lead to robust upper bounds on  $N_\nu$

$$N_\nu < 7 - 17 \quad (7)$$

which are much weaker than that given from BBN data, the right hand side of equation (6) !

- *iii)* Adding large scale structure data to CMBA data Hannestad [20] gives a non trivial lower bound:

$$N_\nu > 1.5 \text{ (95\% CL)} \quad (8)$$

which is the first independent indication of the presence of a cosmological neutrino background, predicted by the standard model, and already seen in BBN data, the left hand side of equation (6).

- *iV)* It seems that there is no significant indication of non standard physics -i.e. no *new physics*- contributing to  $N_\nu$  at the recombination epoch [19] [20].

## 3 Constraints on dark energy

Recent observations [4] [5] of type Ia-supernovae indicate that the Universe may be presently dominated by an additional *dark energy* with a negative pressure such that the Universe is presently accelerating (see also [6]). Combined observations of type Ia-supernovae [4], CMBA [25] and cluster evolution [26] for which the results have been done in the form of likelihood contours in the  $\Omega_M$  and  $\Omega_\Lambda$  plane are reported in Fig. (2).

$\Omega_M$  and  $\Omega_\Lambda$  are defined by

$$\Omega_M = \frac{8\pi G\rho_o}{3H_o} , \quad \Omega_\Lambda = \frac{\Lambda}{H_o} \quad (9)$$

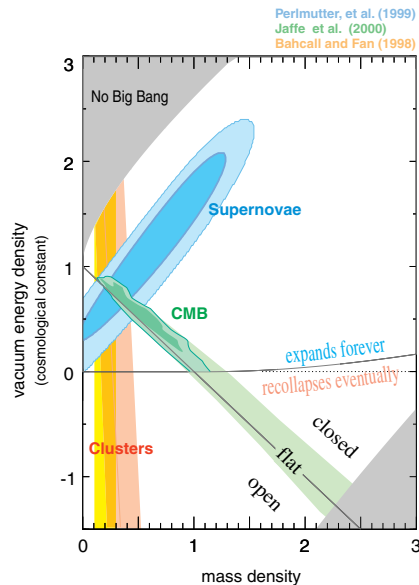


Figure 2: From [7], Confidence regions in the  $(\Omega_M - \Omega_\Lambda)$  plane for high  $z$ -supernovae (see Perlmutter et al. [4]), CMBA [25]) and cluster evolution (Bahcall & Fan [26]) measurements. The consistent *overlap* is a strong indicator for the existence of  $\Omega_\Lambda$ , i.e. of a cosmology constant or dark energy.

where the index  $o$  refers to the present epoch,  $\rho$ ,  $H$  and  $\Lambda$  being respectively, the energy density, the Hubble parameter and the cosmological constant -see [6] for instance.

Let us recall that the Friedman-Lemaitre equation can be written as

$$\Omega_M + \Omega_\Lambda + \Omega_k = 1 \quad (10)$$

with a term of matter plus radiation  $\Omega_M$ , a term of *dark energy*  $\Omega_\Lambda$  and a curvature term such that

$$\Omega_k = \frac{k}{R_o^2 H_o^2} \quad (11)$$

where  $R$  is the cosmic scale factor and  $k$  is the curvature constant.

*What is the nature of this dark energy ?* This is the present challenge for cosmology and particle physics. The simplest interpretation of this dark energy is the *cosmological constant*  $\Lambda$  (vacuum energy) for which the equation of state:

$$w \equiv \frac{P}{\rho} \quad (12)$$

is equal to  $-1$ .

It is important to know if this cosmological *constant*, as inferred by observations, is truly constant or if the observations point out some form of cosmic evolution often called *quintessence*  $Q$ , for which the equation of state  $w_Q$  is such that:

$$-1 \leq w_Q \leq 0. \quad (13)$$

In this case, the vacuum energy is the result of a scalar field  $Q$  slowly evolving along an effective potential or getting trapped in a local minimum and which only interacts with the other fields via gravity- In any case -cosmological constant or quintessence- one is faced with two problems:

- *i)* a fine tuning problem: why the vacuum energy, is so small ? From particle physics, one might expect:  $\Lambda/8\pi G \sim m_{plank}^4$ , and it is off by about 120 orders of magnitude.
- *ii)* a cosmic coincidence problem: why  $\Omega_M$  and  $\Omega_\Lambda$  are nearly equivalent now ?

Since  $w$  is, in general, time vrying, the first step toward solving the dark energy problem is to determine  $w(t)$  or  $w(z)$ .

Before considering some models of quintessence, let us only recall that:

- • for the case where the dark energy is the cosmological constant  $\Lambda$ :

$$w_\Lambda = -1 \quad (14)$$

- • some authors -for instance, Huey et al. [27]- introduce an effective (constant) equation of state  $w_{eff}$  defined by:

$$w_{eff} \sim \frac{\int \Omega_Q(z) \omega(z) dz}{\int \Omega_Q(z) dz} \quad (15)$$

- • for topological defects:

$$w_{string} \sim -\frac{1}{3} \text{ and } w_{wall} \sim -\frac{2}{3} \quad (16)$$

### 3.1 On Quintessence Models

Many quintessence effective potentials exist in the litterature -see, for instance Weller & Albrecht [28]. Here, let us only mention:

- • The cosmological tracker solutions [29] [30]  
with, in particular, the inverse tracker potential of Ratra & Peebles [31]

$$V(Q) = M^{(4+\alpha)} Q^{-\alpha} \quad (17)$$

where  $M$  and  $\alpha$  are parameters such as  $\Omega_Q \sim 2/3$  at present. The tracker solutions evolve on a common evolutionary track independent of the initial conditions. All the tracker models have in common that the density in the dark energy at late times dominates over all the other density contributions and therefore the expansion of the Universe starts accelerating.

• • The Supergravity Potential:

$$V_{SUGRA}(Q) = M^{(4+\alpha)} Q^{-\alpha} \exp\left[\frac{1}{2}\left(\frac{Q}{M_{pl}}\right)^2\right], \quad (18)$$

which is related to the supersymmetry breaking -see in particular Binetruy [32], Brax & Martin [33].  $M$  and  $\alpha$  are chosen such that the supersymmetry breaking occurs above the electroweak scale. A discussion on this potential is found in Kolda & Lyth [34].

In all of these models, the energy density of the field  $Q$  is given by the kinetic and potential components:

$$\rho_Q = \frac{1}{2} \dot{Q}^2 + V(Q) \quad (19)$$

while the pressure is given by the difference

$$P_Q = \frac{1}{2} \dot{Q}^2 - V(Q). \quad (20)$$

Moreover, we assume that the field  $Q$  is homogeneous on large scales. Therefore the equation of state of the quintessence is given by:

$$w_Q = \frac{P_Q}{\rho_Q}. \quad (21)$$

Fig. (5) in Weller & Albrecht [28] shows the evolution -in the range of redshift  $[0 - 2]$ - of the equation of state of the dark energy component:

$$w_Q = w_Q(z) \quad (22)$$

for all of these models they discuss in [28] and, in particular, for the two potentials considered here, Eqs (17) and (18).

### 3.2 Constraints on the equation of state of dark energy

We have seen that searches for SNIa at high  $z$  have already provided a strong evidence for an accelerating present Universe [4], [5], [6]. By analyzing a simulated data set as might be obtained by the proposed SNAP satellite [7], Weller & Albrecht [35] claim that it will be possible to discriminate among different dark energy solutions.

Fig. (3) shows the separation of three dark energy models in the  $(\Omega_M - w_o)$  plane where  $w_o$  is such that  $w = w_o + w_1 z$ , although Maor et al. [36] show that this method is indeed very limited.

However, as already seen through the Fig. (2), the result can be better by combining SNIa constraints with other complementary measurements. A low- $z$  measurement such as a cluster survey, an intermediate- $z$  measurement such as a SNIa survey and a high- $z$  measurement such as CMBA measurements can provide complementary constraints.

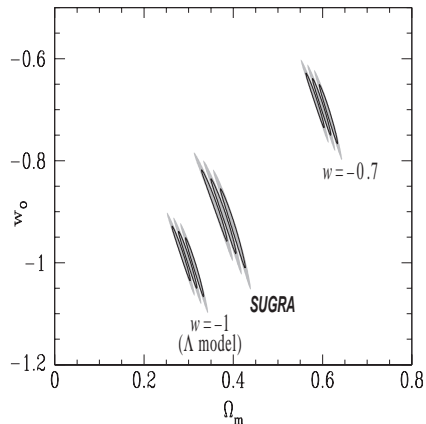


Figure 3: From Weller & Albrecht [35], separation of three dark energy models in the  $(\Omega_M - w_o)$  plane.

Fig. (4) from Hu et al. [37] and Fig. (5) from Huterer & Turner [40] indicate how the constraints from several measurements would constrain a model when the Universe is assumed flat ( $\Omega_k = 0$ ) and  $\omega$  is supposed to be constant

Let us also note that the use of cluster evolution for constraining cosmological parameters is not a new idea; in particular, in 1992 Oukbir & Blanchard [42] introduced it and more recently in 2001, Sadat & Blanchard [43], using it again, find a value of  $\Omega_m$  much higher than  $1/3$ .

Of course, the three combined measurements will first confirm or infirm the existence of dark energy and then -in the case of a confirmation- will give information on its nature by measuring or constraining its equation of state.

## 4 Conclusion

We have seen that:

- *i)* The accurate determination of the primeval deuterium abundance pins down the baryon density of the Universe:  $\Omega_B h^2 \sim 0.02$ . New CMBA data (BOOMERANG, MAXIMA, DASI) lead also to  $\Omega_B h^2 \sim 0.02$  and can significantly constrain neutrino physics if an additional cosmological constrain is imposed. The precision of CMBA measurements will be further improved by MAP and PLANCK. These new observations will thus offer new opportunities to detect or constrain new neutrino physics in the early Universe.
- *ii)* While luminosity-distance measurements of type Ia SN calibrated candles have recently shown that our Universe is accelerating now, the resented question is: what is the dark energy ? Particle physics theory proposes



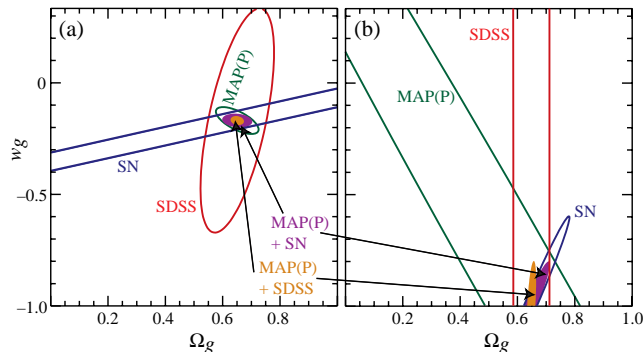


Figure 4: From Hu et al. [37], here  $\Omega_g = \Omega_Q = 1 - \Omega_M$ , confidence regions in the  $(\Omega_g - w_g)$  plane from CMB, SN and large scale structure survey (68 % CL). Here SN means constraints of a supernova program such as SNAP [7], SDSS means constraints of Sloan Digital Sky Survey [38], MAP means constraints of the MAP satellite [39]; (P) means polarization information. (a): Left curves,  $w_g = w_Q = -1/6$ ,  $\Omega_M \sim 1/3$ . (b): Right curves,  $w_g = w_Q = -1$ ,  $\Omega_M \sim 1/3$ . Note the complementarity nature of the data sets.

a number of alternatives to a non-zero vacuum energy/cosmological constant: quintessence in particular.

With future CMBA measurements (MAP, PLANCK) it should be possible to measure a constant equation of state of dark energy within a 10-30 % accuracy. To determine  $\omega$  to 5 % and to begin to probe a time-varying equation of state requires also a large SNIa survey (such as SNAP) and a count of rich clusters of galaxies or a high-redshift survey of galaxies such as DEEP2 [44].

The research on the nature of dark energy, however, is still in a nascent stage. Over the next decade a variety of new strategies and more precise applications of old strategies could very well answer this question once and for all.

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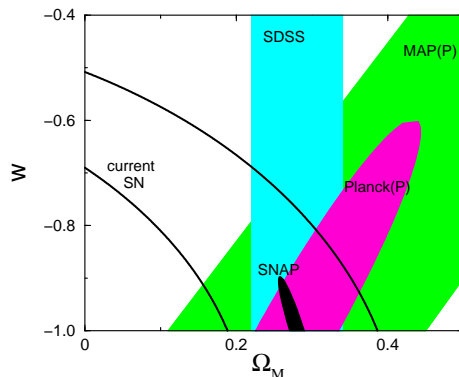


Figure 5: From Huterer & Turner [40], Confidence regions in the  $(\Omega_M, w)$  plane for the case b) of Fig. (4). Here, SDSS, MAP, P have the same meaning as Fig. in (4b). SNAP means constraints of the SNAP satellite [7], current SN means present constraints using about 50 SNIa, PLANCK means constraints of the PLANCK satellite [41].

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